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Femtocell as a Relay: An Outage Analysis

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***Abstract*—Femtocells promise to increase the number of users served in a given macrocell by creating indoor hotspots through the deployment of home base stations (HBSs) connected to the mobile operator network via cheap backhaul links (i.e., the Internet). However, the interference created by femtocell transmissions may critically impair the performance of the macrocell users. In this paper, a novel approach to the operation of HBSs is proposed, whereby the HBSs act as relays with the aim of improving transmission reliability for femtocell users and, possibly, also macrocell users. The proposed approach enables cooperative strategies between HBS and macrocell base stations (BSs), and is unlike the conventional deployment of femtocells where HBSs operate as isolated encoders and decoders.**

The performance advantages of the proposed approach are evaluated by studying the transmission reliability of macro and femto users for a quasi-static fading channel in terms of outage probability and diversity-multiplexing trade-off for uplink and, more briefly, for downlink. Overall, the analytical and numerical results lend evidence to the fact that operating femtocells as relays may potentially offset the performance losses associated with the presence of additional active users in the cell due to femtocells and even provide overall performance gains.

***Index Terms*—Cellular systems, femtocells, outage probability, diversity-multiplexing trade-off, cooperative transmission.**

I. Introduction

FEMTOCELLS are often seen as an easy fix to the problem of increasing network coverage in cellular systems. This is mostly due to the availability of cheap backhaul connections between the home base stations (HBSs), installed by the subscribers in their premises, and the operator's network, in the form of last-mile links followed by the Internet. The two basic operating modes of HBS are *open-access* (OA), whereby all users have the same privileges in accessing the HBS, and *closed-access* (CA), for which only the subscriber's devices are allowed to access the HBS [1].

Current femtocell deployments dictate that the HBS act essentially as an independent base station (BS). In particular, focusing on the uplink (mobile-to-BS), each HBS is required to decode the intended users and to pass the decoded (hard) information, along with necessary control signalling, to the mobile operator networks via the backhaul links. It is noted that the intended users are the subscriber's devices, typically located indoors, and possibly also macrocell users, typically located outdoors. We will refer to two classes of users as

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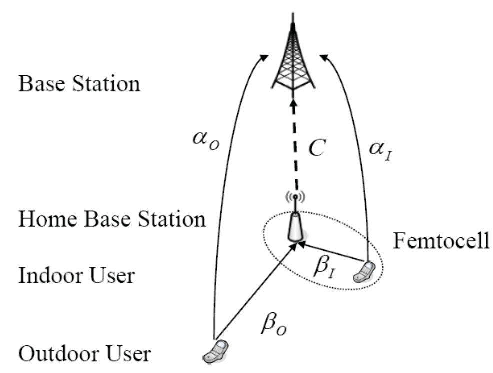

Fig. 1. Uplink of a macrocell overlaid with a femtocell with one indoor (femtocell) and one outdoor (macrocell) user. An out-of-band link (e.g., last-mile link) connects the HBS to the BS.

indoor and *outdoor users* for simplicity. The advantage of deploying conventional femtocells stems from the fact that the presence of a decoder, the HBS, in the vicinity of the users to be decoded, allows devices to transmit at a reduced power. However, on the negative side, allowing more indoor users to transmit, femtocells may possibly affect the quality of service of the existing macrocell users communicating directly to the macrocell BS, due to the additional interference. There is clearly a trade-off between the additional interference created by femtocell transmissions and the increased system capacity due to the larger number of users served. This has been explored in a number of works such as [2][3][4] (see below).

A. Contributions

This paper explores the possibility to operate the femtocells in a different way than merely as additional BSs or equivalently, focusing on the uplink, as decoders. In particular, we look at the performance advantages of *operating HBSs as relays*. To elaborate, consider the scenario in Fig. 1, which depicts a single cell with a single femtocell and two users, one indoor and one outdoor. The standard deployment discussed above dictates that the HBS decodes the signal from the indoor user and, in case of OA femtocells, possibly also the outdoor user. The decoded information is sent to the mobile operator network via the backhaul link. Instead we propose to implement the decoder of both indoor and outdoor users at the mobile operator network. This way, the decoder has access to both the signal received by the macrocell BS and the bits sent by the HBS on the backhaul link. Moreover, the HBS can be used as a relay, that is, it can be used to provide "soft" information regarding the received signal to the decoder in order to facilitate decoding. Notice that the HBS communicates to the decoder via the backhaul link. This is illustrated in Fig. 1, where for simplicity of representation, the decoder is depicted as the macrocell BS.

The above novel framework of "HBSs as relays" is in practice enabled by two main modifications of the traditional femtocell architecture, which seem within the reach of current technology. One is the routing of the information sent on the backhaul link by the HBS towards a decoder that performs joint decoding of indoor and outdoor users. The second is the possibility to send potentially soft information from the HBS to the mobile operator network. This is unlike the current deployment where HBSs are required to format the transmitted information as the decoded (hard) information from the intended users [1].

To assess the performance advantages of operating the HBSs as relays, we analyze the transmission reliability in the system of Fig. 1 over quasi-static fading channels. Specifically, we first derive analytical expressions for the outage probability of uplink transmission with relaying techniques, inspired by both CA and OA modes, for fixed transmission rates and SNR. We then address the diversity-multiplexing tradeoff (DMT) [5][6] in both scenarios, thereby considering the regime of high SNR and of different transmission rate scalings (multiplexing gains). We demonstrate that the framework of *femtocells as relays* has the potential to solve the issue identified above with the standard deployment of femtocells. In particular, it allows more users to be served with potentially no performance disadvantage, in terms of reliability, for the existing macrocell (outdoor) users. In fact, by choosing appropriate relaying techniques, performance advantages can be accrued for both indoor and outdoor users. Finally, we briefly extend the conclusions above to the downlink scenario.

B. Related Work

Related analyses of the performance of cellular systems in the presence of femtocells can be found in [2] and references therein. Especially related are [3][4]. In [3], the DMT analysis of a single-macrocell single-femtocell system is presented, by modelling the latter as a "Z-interference channel" so that no interference is assumed between femtocell user and BS. In [4] a performance comparison of OA and CA femtocells is provided in terms of achievable throughputs, accounting for the random location of the femtocell within a cell, but not for fading. In both works, one key assumption is that the HBS decodes the signal from the femtocell user and, for OA (in [4]), also the signal of the macrocell users assigned to the HBS. In this work, instead, we do not impose this conventional restriction and allow the HBS to operate, more generally, as a relay for the macro-BS, which is the intended decoder for both femtocell and macrocell users. We remark that, using this standpoint, performance of CA and OA femtocells in multicell systems in the absence of fading is studied in [7].

Finally, we note that this work was partially presented in the conference paper [15]. As compared to [15], here we propose an alternative transmission scheme based on compress-and-forward, whose benefits will be discussed below, present more extensive numerical results and discuss also the downlink.

Notation: The notation $\doteq$ is the exponential equality $f(\rho)\doteq\rho^d$ if $\lim_{\rho\to\infty} f(\rho)/\rho = d$, and $\dot{\leq},\dot{\geq}$ are similarly defined. $(x)^+$ denotes $\max\{x,0\}$ and $C(x)=\log_2(1+x)$.

II. System Model

Consider a macrocell, served by single BS which is overlaid with a femtocell served by a HBS, as depicted in Fig. 1. For simplicity, we focus our discussion on the case of a single active indoor (i.e., femtocell) user and a single active outdoor (i.e., macrocell) user per cell. We first consider uplink transmission, where indoor and outdoor users transmit one message per transmission block with rates R_I and R_O (bits/ channel use), respectively. Downlink will be discussed in Sec. VI. Assuming time synchronization, the discrete-time received signals for the BS and HBS at time $t=1,...,n$ are

$$y_{B,t} = \sqrt{\alpha_I}h_{IB}x_{I,t}+\sqrt{\alpha_O}h_{OB}x_{O,t}+z_{B,t}, \quad (1)$$
$$y_{H,t} = \sqrt{\beta_I}h_{IH}x_{I,t}+\sqrt{\beta_O}h_{OH}x_{O,t}+z_{H,t}, \quad (2)$$

where subscripts distinguish indoor ("I") user, outdoor ("O") user, HBS ("H") and BS ("B"); α_i,β_i are the user i-to-BS and user i-to-HBS average channel power gains respectively, $i\in\{O,I\}$; h_{iB},h_{iH} model independent quasi-static Rayleigh fading unit-power channels (i.e., h_{iB},h_{iH} are complex Gaussian with unit power); $x_{i,t}$ represents user i's transmitted symbol, which is assumed to satisfy the block power constraint

$$\frac{1}{n}\sum_{t=1}^{n}E\left[|x_{i,t}|^2\right]\leq\rho_i, \quad (3)$$

where we set $\rho_i=\rho$ since any difference in power can be captured by the average channel gains α_i,β_i; and, finally, $z_{B,t}$, $z_{H,t}$ are the independent unit-power complex Gaussian noise sequences at the BS and HBS respectively. Channel state information is assumed only at the receivers. The HBS is connected to the BS via a last-mile link (e.g., DSL or cable) followed by the Internet, which we model here as an out-of-band (i.e., orthogonal) link of capacity C bits/ channel use. The HBS receives (2) for $t=1,...,n$ and, based on this, decides the nC bits to be sent to the BS. The BS decodes both messages of indoor and outdoor users based on the signal (1) for $t=1,...,n$ and the bits received from the HBS.

It is noted that the considered model can be classified as a multiple access channel with an out-of-band relay following standard nomenclature (see, e.g., [12]). For comparison, an outage analysis of the corresponding scenario with in-band relaying can be found in [16] and references therein. An out-of-band relay channel with a single user and without fading is instead studied in [11].

A. Transmission Strategies

Inspired by the classification of HBS operation modes into OA and CA, we consider the following transmission schemes.

Closed Access (CA): The femtocell attempts to decode the indoor user's signal and treats the outdoor user's signal as noise. Upon successful decoding of the indoor user's message, the femtocell dedicates a rate up to the total backhaul capacity C for transmission of such message towards the BS. If decoding is not successful, the backhaul link is not used. Notice that the scheme is based on Decode-and-Forward (DF) [8].

$$P_{B,none}(R_I,R_O) = 1-\exp\left(-K_{B,O}\right) + \frac{\exp\left(-\frac{2^{R_O+R_I}-1}{\rho}\right)\left(\exp(-K_{B,O}(\alpha_O-1))-\exp\left(-2^{R_I}K_{B,O}\alpha_O(\alpha_O-1)\right)\right)}{\alpha_O-1}$$
$$+\frac{\exp\left(\frac{1}{\alpha_O\rho}\right)\left(\exp\left(-\left(\frac{\zeta_B}{\alpha_O\rho}-K_{B,O}\right)\right)-\exp\left(-2^{R_O}\left(\frac{\zeta_B}{\rho}-K_{B,O}\alpha_O\right)\right)\right)}{\left(2^{R_O}-1\right)^{-1}\left(2^{R_O}-1+\zeta_B\right)} + \exp\left(-K_{B,I}\right)\left(\exp\left(\frac{K_{B,O}}{G_{IB}}\right)G_{IB}\right), \quad (4)$$

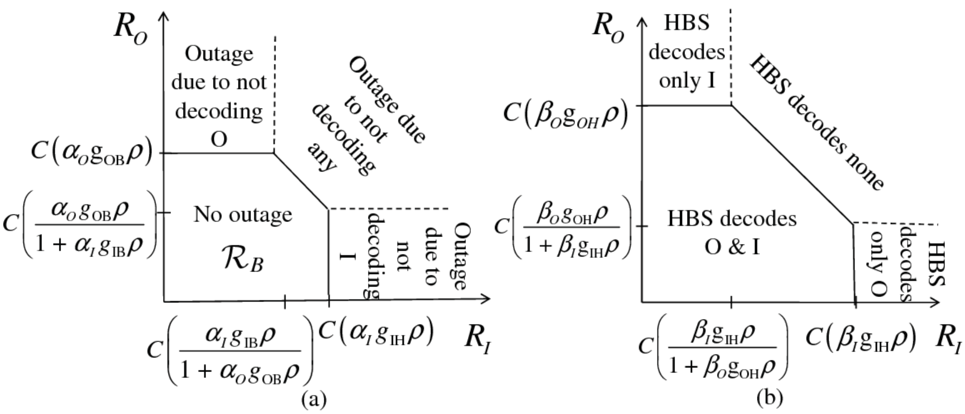

Fig. 2. Illustration of the achievable regions and corresponding outage events for (a) BS and (b) HBS of a CA femtocell.

Open Access (OA): The femtocell attempts to decode both the indoor and the outdoor users' signals. If decoding is successful on both messages, the femtocell transmits up to γC bits/ dim for the indoor user's message and up to $(1-\gamma)C$ bits/ channel use for the outdoor user's signal, where $0 \leq \gamma \leq 1$ determines the fraction of the capacity allocated for each message. If decoding is successful only on one message, the HBS dedicates rate up to the total backhaul capacity C for transmission of such message towards the BS. If decoding is not successful, the backhaul link is not used. This scheme is also based on DF.

Compress-and-Forward (CF): The HBS compresses the received signal from the indoor and outdoor users to C bits/ channel use using the scheme proposed in [9], which improves on the standard compress-and-forward (CF) scheme [8]. It is noted that, with CF, the HBS implicitly serves both indoor and outdoor users in a similar fashion for the OA scheme.

We will analyze the performance of CA, OA and CF femtocells in the uplink in terms of outage probability (for fixed transmission rates) in Sec. III and DMT in Sec. IV, respectively.

III. Outage Analysis

In this section, we analyze the probability of outage under the assumption of fixed rates R_I and R_O, channel power gains α_i, β_i and power ρ. The outage probability is defined as the probability that *at least one* of the messages from the indoor and/or outdoor users is not successfully decoded at the BS (i.e., common outage event).

Using the law of total probability, the outage probability for OA can be computed as follows

$$P_{out}^{OA} = P_{H,OI}P_{out|OI} + P_{H,O}P_{out|O} + P_{H,I}P_{out|I} + P_{H,none}P_{out|none}, \quad (5)$$

where $P_{H,OI}$, $P_{H,O}, P_{H,I}$ are the probabilities of successful decoding at the HBS of both outdoor and indoor messages ($P_{H,OI}$), of the outdoor message only ($P_{H,O}$), and of the indoor message only ($P_{H,I}$), respectively; $P_{H,none}$ is the probability of decoding no message at the HBS; and, finally, $P_{out|OI}$, $P_{out|I}$, $P_{out|O}$, $P_{out|none}$ denote the outage probability (at the BS) conditioned on the corresponding decoding events at the HBS (e.g., $P_{out|OI}$ is the outage probability conditioned on the HBS decoding both messages).

The outage probability for CA can be similarly found as

$$P_{out}^{CA} = P_{H,I}P_{out|I} + P_{H,none}P_{out|none}, \quad (6)$$

where $P_{H,I}$ and $P_{H,none}$ are similarly redefined for CA (notice that $P_{H,OI} = P_{H,O} = 0$ for CA). Calculation of the decoding probability at the HBS will be detailed below for CA and OA, while outage probability for CF will be detailed in Sec. III-C.

For the evaluation of the conditional outage probabilities at the BS, definition of the following quantity turns out to be useful. Denote as $P_{out}(R_I, R_O)$, the probability of outage for a BS decoder based only on the received signal (1) for $t = 1, ..., n$, i.e., without accounting for the bits received from the HBS. The set of rates that can be reliably decoded by such decoder is given by the capacity region of the multiple access channel (1), which is $\mathcal{R}_B$=$\{(R_O, R_I)$: $R_O \leq C(\alpha_O g_{OB}\rho)$, $R_I \leq C(\alpha_I g_{IB}\rho)$, $R_O + R_I \leq C((\alpha_I g_{IB} + \alpha_O g_{OB})\rho)\}$, with $g_{ij} = |h_{ij}|^2$, and is sketched in Fig. 2-(a). Accordingly, by extending the analysis in [10] to multiple access channels with unequal channel gains, we obtain $P_{out}(R_I, R_O) = \Pr[(R_O, R_I) \notin \mathcal{R}_B]$ as

$$P_{out}(R_I, R_O) = P_{B,I}(R_I, R_O) + P_{B,O}(R_I, R_O) + P_{B,none}(R_I, R_O), \quad (7)$$

where $P_{B,I}(R_I, R_O)$, $P_{B,O}(R_I, R_O)$, and $P_{B,none}(R_I, R_O)$ are the outage probabilities at the BS due to not decoding the outdoor message, not decoding indoor message, and not

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decoding any of the messages, respectively, and can be calculated as

$$P_{B,I}(R_I,R_O) = G_{IB}\exp\left[(-K_{B,I}) - \exp\left(-\left(\frac{K_{B,O}}{G_{IB}}+K_{B,I}\right)\right)\right], \quad (8)$$

and (4) with definitions $G_{ij} = \left(\left(2^{R_i}-1\right)\zeta_j+1\right)^{-1}, K_{B,i} = \left(2^{R_i}-1\right)/(\alpha_i\rho)$ with $i\in\{I,O\}$, $j\in\{B,H\}$ and $\zeta_B = \alpha_O/\alpha_I$. $P_{out,O}(R_I,R_O)$ is the same as $P_{out,I}(R_I,R_O)$ with switched subscripts "I" and "O".

Remark 1: For the special case of the symmetric channel gains, i.e., $\zeta_B = 1$, the above probabilities reduce to eq. (15)-(17) of [10].

A. Closed Access (CA)

In this section we evaluate the outage probability (6) for CA. Recall that, with CA, the HBS decodes the indoor user's message and treats the outdoor user's message as (Gaussian) noise of power $\beta_O\rho$. Moreover, upon decoding, the HBS provides up to C bits of the message of the indoor user to the BS. This can be seen to reduce the effective rate of the indoor message to be decoded at the BS to $(R_I - C)^+$ (see, e.g., [11]). This leads to the following.

Proposition 1: The outage probability with a CA femtocell is given by (6), where

$$P_{H,none} = 1 - G_{IH}\exp\left(-K_{H,I}\right), \quad (9)$$
$$P_{out|I} = P_{out}((R_I - C)^+, R_O), \quad (10)$$
$$\text{and } P_{out|none} = P_{out}\left(R_I,R_O\right), \quad (11)$$

with $G_{IH} = \left(\left(2^{R_I}-1\right)\zeta_H + 1\right)^{-1}$, $K_{H,i} = \left(2^{R_i}-1\right)/(\beta_i\rho)$, $\zeta_H = \beta_O/\beta_I$ and $P_{H,I} = 1 - P_{H,none}$.

Proof: Probability $P_{H,none}$ is given by $P_{H,none} = \Pr\left[R_I > C\left(\frac{\beta_I g_{IH}\rho}{1+\beta_O g_{OH}\rho}\right)\right]$, since HBS treats the outdoor user as noise, which can be easily calculated using the fact that g_{OH} and g_{IH} are exponentially distributed. Moreover, the outage probability $P_{out|I}$ at the BS, conditioned on the HBS decoding the indoor user message, is given by $P_{out}((R_I - C)^+, R_O)$ based on the discussion above. □

B. Open Access (OA)

With OA, the HBS attempts to decode both the messages of indoor and outdoor users. Therefore, with OA, the performance is not adversely affected by the outdoor's user interference on the HBS, unlike for CA. Moreover, following the discussion above, the HBS is able to reduce the effective rates to be decoded at the BS to $(R_I - (1-\gamma)C)^+$ and $(R_O-\gamma C)^+$ if both messages are decoded a the HBS, while $\gamma = 0$ or $\gamma = 1$ if only the indoor or only the outdoor messages, respectively, are decoded at the HBS.

Proposition 2: The outage probability with an OA femtocell is given by (5), where $P_{H,I}$, $P_{H,O}$ and $P_{H,none}$ are the same as $P_{B,I}(R_I,R_O)$, $P_{B,O}(R_I,R_O)$, and $P_{B,none}(R_I,R_O)$ with α_O, α_I, ζ_B and $K_{B,i}$ replaced with β_O, β_I, ζ_H, and $K_{H,i}$ respectively, and $P_{H,OI} = 1 - P_{H,I} - P_{H,O} - P_{H,none}$. Moreover, we have

$$P_{out|OI} = P_{out}((R_I - (1-\gamma)C)^+, (R_O-\gamma C)^+), \quad (12a)$$
$$P_{out|O} = P_{out}(R_I,(R_O - C)^+), \quad (12b)$$
$$P_{out|I} = P_{out}((R_I - C)^+, R_O), \quad (12c)$$
$$P_{out|none} = P_{out}(R_I,R_O), \quad (12d)$$

for some $0\le\gamma\le 1$.

Proof: The probabilities of successful decoding at the HBS can be evaluated from Fig. 2-(b) similarly to [10]. For instance, the probability of decoding only the indoor user is given by

$$P_{H,I} = \Pr\left[R_O > C\left(\beta_O g_{OH}\rho\right),\ R_I \le C\left(\frac{\beta_I g_{IH}\rho}{1+\beta_O g_{OH}\rho}\right)\right]. \quad (13)$$

The other terms follow from the discussion above. □

C. Compress-and-Forward (CF)

With CF, the HBS does not decode, but merely forwards soft information about the received signal to the BS. We consider a CF technique based on the noisy network coding strategy of [9]. This choice is dictated by the fact that this scheme is known to perform better in terms of outage probability with respect to standard CF techniques [12]. From [9], we can easily derive that the following rate region is achievable for given channel gains by such scheme:

$$\begin{aligned}\mathcal{R}_B^{CF} &= \{(R_I,R_O):\\ R_O &\le \min\left\{C\left(\left(\frac{\beta_O g_{OH}}{2}+\alpha_O g_{OB}\right)\rho\right),\right.\\ &\qquad \left. C\left(\alpha_O g_{OB}\rho\right) + [C-1]^+\right\}, &(14a)\\ R_I &\le \min\left\{C\left(\left(\frac{\beta_I g_{IH}}{2}+\alpha_I g_{IB}\right)\rho\right),\right.\\ &\qquad \left. C\left(\alpha_I g_{IB}\rho\right) + [C-1]^+\right\}, &(14b)\\ R_O + R_I &\le \min\left\{C\left(\rho\mathbf{H}\mathbf{H}^\dagger\right), C\left(\left(\alpha_O g_{OB} + \alpha_I g_{IB}\right)\rho\right)\right.\\ &\qquad \left. +[C-1]^+\right\}\}, &(14c)\end{aligned}$$

where $\mathbf{H} = [\mathbf{h}_O\ \mathbf{h}_I]$, $\mathbf{h}_O = \left[\sqrt{\alpha_O}h_{OB}\ \ \sqrt{\beta_O}h_{OH}\right]^T$, $\mathbf{h}_I = \left[\sqrt{\alpha_I}h_{IB}\ \ \sqrt{\beta_I}h_{IH}\right]^T$. A brief derivation is in Appendix A.

Therefore, the corresponding outage probability is $P_{out}^{CF} = \Pr\left[(R_I,R_O)\notin\mathcal{R}_B^{CF}\right]$. This probability is obtained using Monte Carlo simulations since a closed-form solution appears to be mathematically intractable.

IV. DMT Analysis

Here, we address the DMT analysis of OA, CA and CF. When evaluating the DMT, one assumes asymptotically large power (or signal-to-noise ratio, SNR) ρ and a collection of transmission schemes, one for each ρ, with rates $R_O = r_O\log_2\rho$ and $R_I = r_I\log_2\rho$, with (r_O,r_I) being the corresponding multiplexing gains. We set $r_O = r_I = r$, with r being the *per-user multiplexing gain* and assume that the capacity of the HBS-BS link scales as $C = c\log_2\rho$ for some $c\ge 0$. Notice that the scaling of the backhaul capacity is necessary to obtain meaningful results given the scaling of

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the transmission rates. Moreover, we write the channel power gains $\alpha_i, \beta_i,\ i \in \{O, I\}$ as

$$\alpha_i = \rho^{\bar{\alpha}_i - 1} \text{ and } \beta_i = \rho^{\bar{\beta}_i - 1}, \tag{15}$$

so that $\bar{\alpha}_i$ and $\bar{\beta}_i$ define the scaling of $\alpha_i\rho$ and $\beta_i\rho$ in dB versus the power ρ (see, e.g., [13]). Notice that varying $\bar{\alpha}_i, \bar{\beta}_i$ allows to account for differences in the power gains as measured in dB. This is especially important in the scenario at hand, where indoor and outdoor channels may have significantly different powers. Given the system parameters above, a diversity gain $d(r)$ is achievable if the probability of outage satisfies $P_{out} \dot{\leq} \rho^{-d(r)}$. The following result will be useful.

Lemma 1: Setting $R_O = r_O \log \rho$ and $R_I = r_I \log \rho$, we have $P_{out}(R_O, R_I) \dot{\leq} \rho^{-d_{out}(r_O, r_I)}$, with

$$\begin{aligned} d_{out}(r_O, r_I) &= \min\Big((\bar{\alpha}_I + \bar{\alpha}_O - 2(r_O + r_I))^+, \\ &\qquad (\bar{\alpha}_O - r_O)^+, (\bar{\alpha}_I - r_I)^+ \Big). \end{aligned} \tag{16}$$

Proof: Using the conventional definition $g_{iB} = \rho^{-a_i}$ and $g_{iH} = \rho^{-b_i}$, where a_i and b_i are random variables representing the exponential order of g_{iB} and g_{iH}, it can be proved that the probability density function of a_i, b_i can be written as [5][6]

$$f_{a_i}(x) = f_{b_i}(x) \dot{=} \begin{cases} \rho^{-\infty} = 0, & \text{for } x < 0 \\ \rho^{-x}, & \text{for } x \geq 0. \end{cases} \tag{17}$$

Using the union bound, we easily obtain

$$\begin{aligned} P_{out}(R_O, R_I) \dot{\leq} & \Pr\Big[(r_O + r_I) > \max\Big((\bar{\alpha}_I - a_I)^+, \\ & (\bar{\alpha}_O - a_O)^+\Big)\Big] + \Pr\Big[r_O > (\bar{\alpha}_O - a_O)^+\Big] \\ & + \Pr\Big[r_I > (\bar{\alpha}_I - a_I)^+\Big], \end{aligned} \tag{18}$$

and the result follows from the standard application of Laplace's principle using (17) [5][6].□

A. Closed Access (CA)

Proposition 3: The following DMT is achievable for a femtocell with CA

$$d^{CA}(r) = \min\left\{ d_{out|I},\ d_{H,none} + d_{out|none} \right\}, \tag{19}$$

where

$$\begin{aligned} d_{out|I} &= d_{out}(r, (r-c))^+, & (20)\\ d_{H,none} &= (\bar{\beta}_I - \bar{\beta}_O - r)^+, & (21)\\ \text{and } d_{out|none} &= d_{out}(r, r), & (22) \end{aligned}$$

with definition (16).

Proof: We need to evaluate (6) in the given setting. To this end, we bound $P_{out}^{CA} \leq P_{out|I} + P_{H,none} P_{out|none}$ (using $P_{H,I} \leq 1$) and then find exponential inequalities for the three terms at hand. For instance, the probability of outage at the HBS $P_{H,none}$ satisfies the exponential inequality

$$P_{H,none} \dot{\leq} \Pr\left[r > \left((\bar{\beta}_I - b_I)^+ - (\bar{\beta}_O - b_O)^+ \right)^+ \right] \tag{23}$$

which leads to $P_{H,none} \dot{\leq} \rho^{-d_{H,none}}$ with (21) using the Laplace principle and (17). The other terms $P_{out|I}$ and $P_{out|none}$ can be treated similarly by using Lemma 1 and recalling that, upon detection of the indoor user, the HBS communicates (up to) $C = c \log \rho$ bits/ channel regarding the indoor message.□

B. Open Access (OA)

Proposition 4: The following DMT is achievable for a femtocell with OA

$$\begin{aligned} d^{OA}(r) = \max_{0 \leq \gamma \leq 1} \min\big\{ & d_{out|OI},\ d_{H,O} + d_{out|O},\ d_{H,I} & (24)\\ & + d_{out|I}, d_{H,none} + d_{out|none} \big\}, & (25) \end{aligned}$$

where

$$\begin{aligned} d_{out|OI} &= d_{out}\left((r - \gamma c)^+, (r - (1-\gamma)c)^+ \right), & (26a)\\ d_{out|O} &= d_{out}\left((r-c)^+, r \right), & (26b)\\ d_{out|I} &= d_{out}\left(r, (r-c)^+ \right), & (26c)\\ d_{out|none} &= d_{out}(r, r), & (26d) \end{aligned}$$

and

$$\begin{aligned} d_{H,O} &= \left(\bar{\beta}_I - r \right)^+, & (27a)\\ d_{H,I} &= \left(\bar{\beta}_O - r \right)^+, & (27b)\\ d_{H,none} &= \max\Big\{ \left(\bar{\beta}_I + \bar{\beta}_O - 4r \right)^+, \left(\bar{\beta}_I + \bar{\beta}_O - r \right)^+ \\ & \qquad + \left(\bar{\beta}_O - \bar{\beta}_I - r \right)^+ \Big\} & (27c) \end{aligned}$$

Proof: We bound to the outage probability (5) as

$$\begin{aligned} P_{out}^{OA} \ \dot{\leq}\ & \rho^{-d_{out|OI}} + \rho^{-\left(d_{H,O} + d_{out|O}\right)} \\ & + \rho^{-\left(d_{H,I} + d_{out|I}\right)} + \rho^{-\left(d_{H,none} + d_{out|none}\right)} \end{aligned} \tag{28}$$

where we have used $P_{H,OI} \leq 1$ and defined achievable diversity orders for the remaining individual probabilities in (5) as $P_{out|OI} \dot{\leq} \rho^{-d_{out|OI}}$ and similarly for $d_{out|O}, d_{out|I}, d_{out|none}$. These diversity orders can be obtained by using Lemma 1 and the Laplace principle.□

C. Compress-and-Forward (CF)

In this section, for simplicity, we restrict the results to a scenario with average channel gains characterized by $\bar{\alpha}_O = \bar{\alpha}_I = \bar{\beta}_O = \bar{\beta}_I = 1$. Extension to a more general case turns out to pose some analytical challenges that we do not tackle here, except for the special case discussed below in Remark 2.

Proposition 5: The following DMT is achievable for a femtocell with CF

$$d^{CF}(r) = \min\left\{ 2(1-r)^+, (1-r+c)^+, (2-4r+c)^+ \right\}. \tag{29}$$

Proof: We use the union bound on the probability that any of the inequalities in (14) is not satisfied, and find exponential inequalities for the corresponding three probabilities. For instance, the probability P_I that the first inequality is not satisfied is upper bounded by

$$\begin{aligned} P_I \ \dot{\leq}\ & \Pr\Big[r > \max(\max\left((1-b_I)^+, (1-a_I)^+ \right) \\ & , (1 - a_I + c)^+) \Big]. \end{aligned} \tag{30}$$

The second inequality can be treated in the same way. For the third, we exploit the well-known DMT of a 2×2 MIMO system [5]. Finally, using the Laplace's principle concludes the proof.□

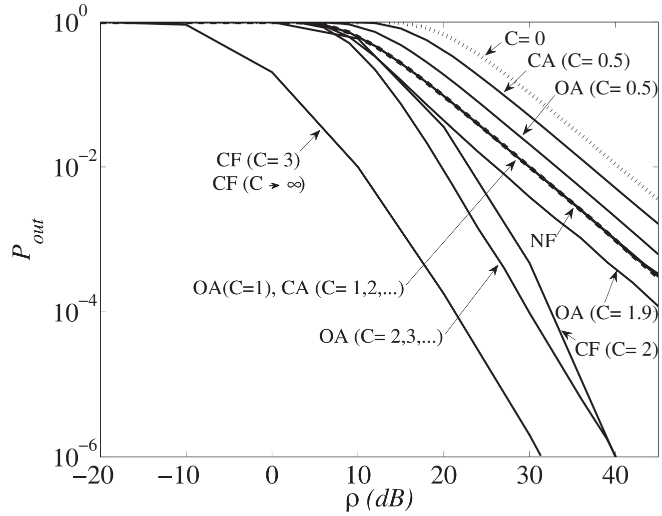

Fig. 3. Uplink probability of outage P_{out} versus ρ for fixed user rates $R_O = R_I = 1$ and different values of backhaul link capacity C for CA, OA and CF femtocells ($\alpha_o = -10dB, \alpha_I = -20dB, \beta_o = 10dB, \beta_I = 20dB$).

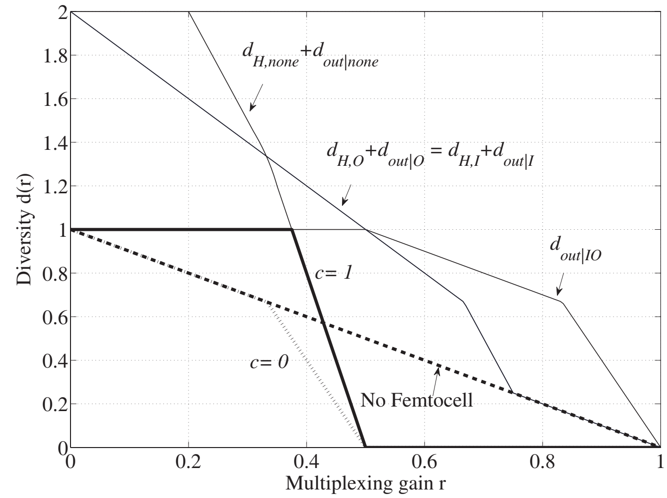

Fig. 4. DMT of the OA scheme ($\alpha_O = \alpha_I = \beta_O = \beta_I = 1, r_O = r_I = r$).

Remark 2: While the general analysis of the effect of different channel gains is complex, here we consider the special case with $\alpha_I = 0$, $\bar{\alpha}_O = \bar{\beta}_O = \bar{\beta}_I = 1$. With this choice, we account for the fact that the power received by the BS from the indoor user can be much smaller than the power received by the HBS from indoor and outdoor users, and by the BS from the outdoor user. For this setting, the achievable DMT for a femtocell with CF can be seen to be given by

$$d^{CF}(r) = \min\left\{(1-r)^+, c, (1-2r+c)^+\right\}. \qquad (31)$$

Comparing (31) with (29) demonstrates the performance loss due to the negligible power received on the link between the indoor user and the BS.

V. Numerical Results and Discussion

In this section, we present some numerical results to substantiate the analysis above. We start by considering the probability of outage P_{out} optimized over γ for a system with fixed rates $R_O = R_I = 1$ (bits/channel use) and different link capacity C (bits/channel use) versus the SNR ρ in Fig. 3. We set channel power gains as $\alpha_O = -10dB, \alpha_I = -20dB, \beta_O = 10dB$ and $\beta_I = 20dB$, so that the indoor user-HBS channel is $40dB$ better than the indoor user-BS channel [1]. Performance as a function of the location of the users is discussed below around Fig. 7 and 8.

Throughout, we compare the outage performance of the proposed schemes with the performance of a scenario, referred to as *"No Femtocell" (NF)*, where the femtocell is not present so that neither the HBS nor the indoor users are in the system. In other words, with NF, the outdoor user communicates directly to the BS and no additional user is active. A further reference scenario of interest is obtained by setting $C = 0$ in our model. In this case, both outdoor and indoor users are active, and the HBS is disabled (e.g., malfunctioning) since it cannot communicate to the BS. It is noted that for $C = 0$, clearly, CA, OA and CF have the same performance.

From Fig. 3, it is seen that allowing the indoor user to transmit with the HBS disabled ($C = 0$) increases the outage probability with respect to the NF case[4]. However, exploiting the HBS-BS backhaul link ($C > 0$), with either CA or OA, enables a significant performance improvement. In fact, for $C \geq 1$, CA performs as well as NF due to the possibility to cancel the indoor user's interference at the BS thanks to relaying by the HBS. Moreover, for OA the performance can even be improved with respect to the NF case, since both indoor and outdoor users benefit from the presence of the HBS. Most notably, for $C > R_I + R_O = 2$, we have an increased diversity order with respect to NF, since outage is in this case prevented as long as either HBS or BS decodes.

Finally, from Fig. 3, we see that if the backhaul capacity C is larger than $R_I + R_O = 2$, while the DF-based technique OA does not further improve its performance, this is not the case with CF. Indeed, CF provides the receiver with information about the received signal at the HBS whose accuracy can be increased as C gets large, while OA cannot further exploit the excess backhaul capacity $C - (R_I + R_O)$. Therefore, as C increases, CF enables the outage probability to decrease down to the performance of an ideal system in which the signal received by the HBS is available at the BS (shown as "CF ($C \to \infty$)" in the figure). This is further discussed below in the terms of DMT. Note that the performance of the ideal system is in practice achieved with reasonably small values of C (here, $C = 3$).

We then consider the DMT analysis. Fig. 4 shows the DMT for the OA femtocell (Proposition 4) for $\bar{\alpha}_O = \bar{\alpha}_I = \bar{\beta}_O = \bar{\beta}_I = 1$, and $c = 1$, compared to the case where the femtocell is turned off $(c = 0)$ and to the NF case. Similar to the discussion above, allowing transmission of the indoor user with $c = 0$ is seen to reduce the achievable diversity for sufficiently large multiplexing gain r with respect to the NF case. In particular, no multiplexing gains $r \geq 0.5$ are achievable at non-zero diversity if $c = 0$. This is well known from the analysis in [5], since when $c = 0$ the scenario at hand boils down to a multiple access channel. Our analysis reveals

[4]Recall that we consider the common outage probability. The individual outage probability for the outdoor user increases as well, albeit less than the common outage probability (not shown here).

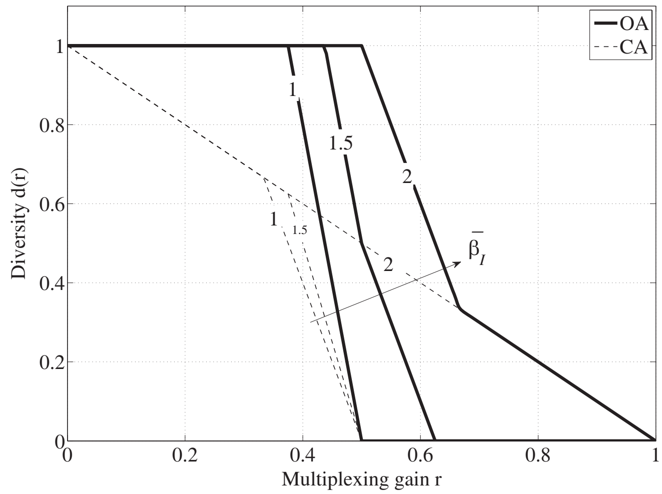

Fig. 5. Comparison between the DMT of the CA and OA schemes ($\alpha_O = \alpha_I = \beta_O = 1, \beta_I = 1, 1.5, 2, r_O = r_I = r$).

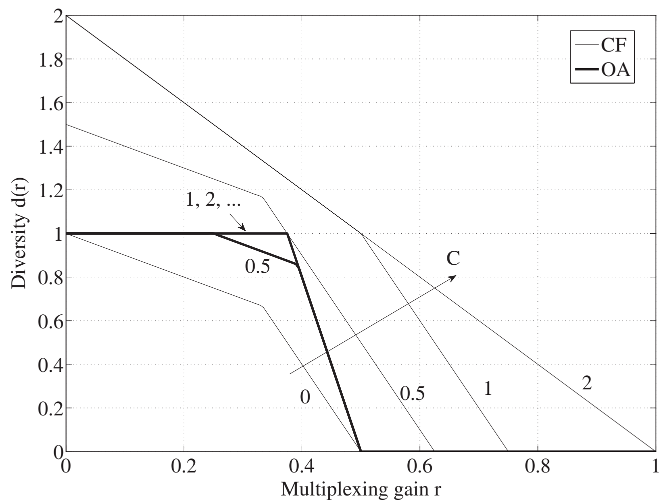

Fig. 6. Comparison between the DMT of OA and CF schemes ($\alpha_O = \alpha_I = \beta_O = \beta_I = 1, r_O = r_I = r$).

that OA with $c = 1$ enables a diversity gain of 1 to be achieved for all multiplexing gains $r \leq 3/8$. This confirms that, with OA, the overall performance of the system, including outdoor users, can be improved.

Fig. 4 also shows the impact of the different error events on the DMT (25) for OA femtocells. In particular, it is seen that for small multiplexing gains r the dominating error event corresponds to the case where the HBS decodes both messages, whereas for larger r the dominating error events is when the HBS decodes no message.

Fig. 5 compares the performance of OA and CA in terms of DMT for $\bar{\alpha}_O = \bar{\alpha}_I = \bar{\beta}_O = 1$, $c = 1$ and different indoor user-to-HBS gain $\bar{\beta}_I$. It is seen that OA outperforms CA unless the multiplexing gain and $\bar{\beta}_I$ are large: In this case, the dominating error event corresponds to decoding no messages at the HBS, which, due to large $\bar{\beta}_I$, turns out to have the same asymptotic probability for both CA and OA. Also notice that with $\bar{\beta}_I = 2$, CA has the same DMT as NF, since correct decoding of the indoor user at the HBS happens with high probability.

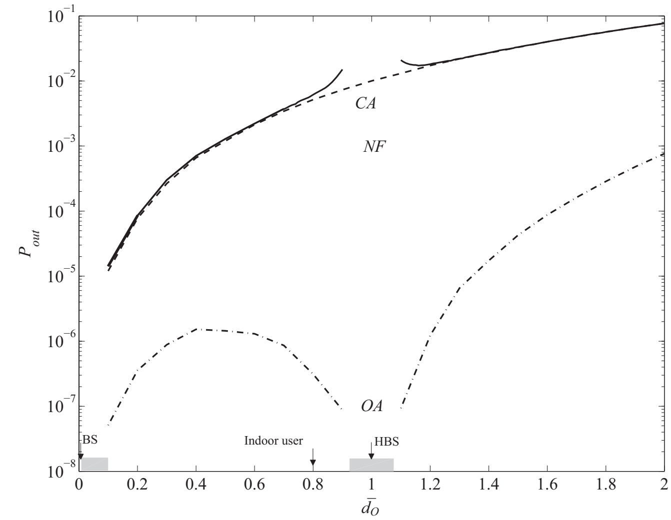

Fig. 7. P_{out} versus the normalized outdoor user-BS distance $\bar{d}_O$ for user rates $R_O = R_I = 1$ and backhaul link capacity $C = 2$ for NF, CA and OA schemes with no power control at the outdoor user ($\eta = 3, \rho = 20dB, d_{HBS} = 10$).

Fig. 6 plots the DMT for CF femtocell (Proposition 5) and $\bar{\alpha}_O = \bar{\alpha}_I = \bar{\beta}_O = \bar{\beta}_I = 1$. It is shown that for c sufficiently large, the performance tends to that of a two user multiple access channel with *two* receiving antennas, which was derived in [14]. This is consistent with the discussion around Fig. 3. Comparing the performance with the OA scheme, it is clear that CF has the ability to exploit large backhaul capacities to improve the system performance as compared to DF-based schemes in terms of both diversity and multiplexing gains.

The discussion above focuses mostly on the impact of the additional interference created by the indoor user on the system performance. Instead, we now provide some further remarks on the role of the interference from the outdoor user to the HBS, and on the near-far effect that may result from power control at the outdoor user. To this aim, we consider a scenario where the BS, HBS, indoor user and outdoor user are on a straight line. Defining as d_{HBS} the BS-HBS distance, we place the indoor user at a normalized distance $\bar{d}_I = d_I/d_{HBS} = 0.8$ so that the normalized indoor user-HBS distance is 0.2. See Fig. 7 and 8 for an illustration. We then vary the normalized outdoor user-BS distance $\bar{d}_O = d_O/d_{HBS}$ in order to study the effect of outdoor-to-femtocell interference.

Fig. 7 and 8 plot P_{out} versus $\bar{d}_O$ for fixed user rates $R_O = R_I = 1$ and backhaul link capacity $C = 2$ for NF, CA and OA with no power control and with power control at the outdoor user, respectively. When no power control is performed, average channel power gains are given as $\alpha_O = 1/d_O^\eta$, $\alpha_I = 1/d_I^\eta$, $\beta_O = 1/|d_O - d_{HBS}|^\eta$ and $\beta_I = 1/(d_{HBS} - d_I)^\eta$ with path loss exponent η. We introduce exclusion zones (dark areas in the figures) around BS and HBS in order to avoid divergence of the received power. Instead, when power control is performed at the outdoor user, the latter is assumed to scale its transmit power so as to enable the BS to receive at an average constant power. This is obtained by setting the channel gains as $\alpha_O = 1$ and $\beta_O = d_O^\eta/|d_O - d_{HBS}|^\eta$, while α_I and β_I are as above. We set $\eta = 3$, $\rho = 20dB$ and $d_{HBS} = 10$.

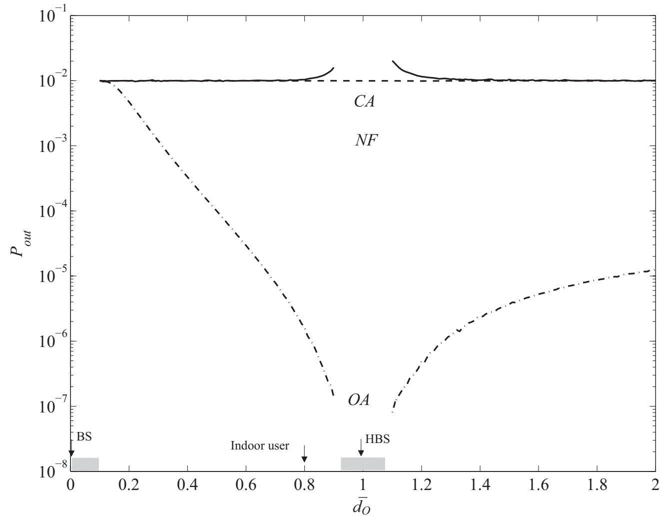

Fig. 8. P_{out} versus the normlized outdoor user-BS distance $\bar{d}_O$ for user rates $R_O = R_I = 1$ and backhaul link capacity $C = 2$ for NF, CA and OA schemes with power control at the outdoor user ($\eta = 3, \rho = 20dB, d_{HBS} = 10$).

From Fig. 7, it is seen that without power control, the performance of the outdoor user when the femtocell is not present (NF) clearly decreases as the distance to the BS $\bar{d}_O$ increases. Moreover, CA is able to accommodate also the indoor user with no performance degradation with respect to NF except when the outdoor user creates excessive interference to the HBS, that is, for $\bar{d}_O$ close to 1. OA is able instead to improve the system performance especially when the outdoor user is either close to the HBS, so that decoding of the outdoor user at the HBS is extremely likely, or close to the BS, which boosts reception at the BS.

With power control at the outdoor user, from Fig. 7, the performance with NF is clearly independent of the distance $\bar{d}_O$. Moreover, CA shows similar gains as discussed above. The effect of power control on OA, instead, depends on $\bar{d}_O$. In particular, if $\bar{d}_O$ is small, the performance of OA is degraded with respect to no power control due to the fact that the HBS receives at a smaller power and is thus not able to effectively decode the outdoor user. Instead if $\bar{d}_O$ is large, the OA performance is improved due to the larger power transmitted by the outdoor user.

VI. Downlink

In this section, we briefly extend the considerations made above for the uplink to the corresponding downlink model, which is shown in Fig. 9. The BS communicates with indoor and outdoor users with rates R_I and R_O, respectively, using the HBS as a possible relay. Power constraints for BS and HBS are both given by ρ and channel gains are defined as for the uplink. Communication between BS and HBS takes place over a backhaul link of capacity C (bits/ channel use). Channel state information is available at both transmitters and receivers, idealizing standard cellular scenarios in which some form of channel state information is typically known at the base stations. Notice that the messages of both users are provided by the network to an encoder that is assumed to be located at the BS for both outdoor and indoor users, unlike the conventional femtocell design in which messages for the indoor users are directly sent to the HBS (recall discussion in Sec. I, which was focused on the uplink).

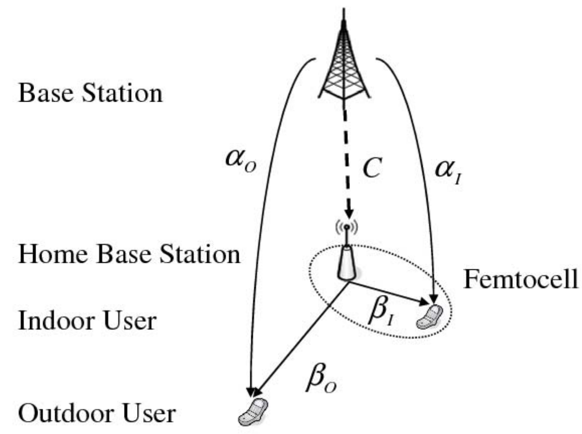

Fig. 9. Downlink of a macrocell overlaid with a femtocell with one indoor (femtocell) and outdoor (macrocell) user. An out-of-band link (e.g., last-mile link) connects the HBS to the BS.

A. Transmission Strategies

For downlink, we consider two DF-based strategies similar to CA and OA for the uplink. We leave extension of the CF to future work. The techniques are based on standard maximum-SNR beamforming and time-division multiplexing.

Closed Access (CA): The encoder at the BS divides the bits (message) intended for the indoor user in two parts, of respective rates R_{I1} and R_{I2} (with $R_I = R_{I1} + R_{I2}$). These, along with the outdoor message, are transmitted in three separate time-slots with appropriate time allocation. The first part of the indoor message, of rate R_{I1}, is sent by the BS directly to the indoor user without the help of the HBS, while the second, of rate R_{I2}, is sent in cooperation with the HBS using beamforming. To enable cooperation, the second part is conveyed to the HBS over the backhaul link prior to transmission to the users, so that we must have that $R_{I2} \leq C$. We take $R_{I2} = \min(C, R_I)$ to maximize the amount of cooperation.

Open Access (OA): While in the CA scheme the HBS operates as a relay only for the indoor user, with the OA scheme, as for the uplink, the relay assists both users. In order to enable cooperation, the BS divides the indoor message as above and performs a similar operation on the outdoor message, producing two submessages of rates R_{O1} and R_{O2} (with $R_O = R_{O1} + R_{O2}$). The first is transmitted only by the BS, while the second is sent cooperatively using beamforming by BS and HBS. The resulting four submessages are transmitted in four separate time-slots with appropriate time allocation. Beamforming by the BS and HBS is performed over the "cooperative" messages of rates R_{I2} and R_{O2} in the corresponding time-slots. As for CA, both "cooperative" messages have to be conveyed to the HBS via the backhaul link. For this purpose, we define a parameter $0 \leq \gamma \leq 1$ so that $R_{I2} = \min(R_I, \gamma C)$ and $R_{O2} = \min(R_O, (1-\gamma)C)$.

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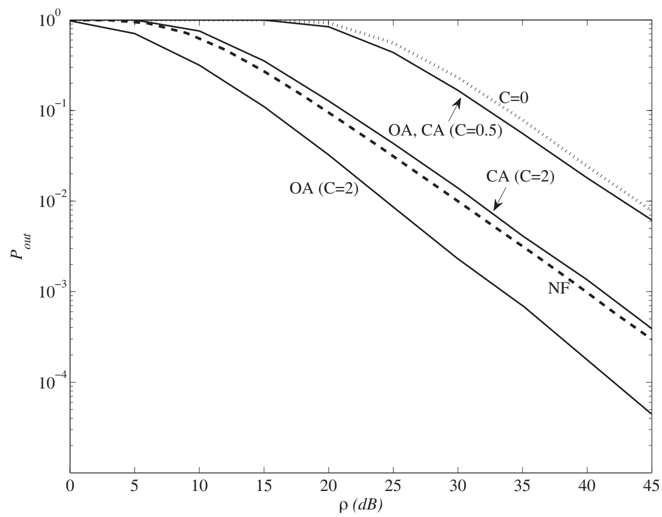

Fig. 10. Downlink probability of outage P_{out} versus ρ for user rates $R_O = R_I = 1$ and different values of link capacity C for CA and OA schemes $(\alpha_o = -10dB, \alpha_I = -20dB, \beta_o = 10dB, \beta_I = 20dB)$.

VII. Outage Analysis

As for the uplink, we define the outage probability as the probability that *at least one* of the broadcast messages from the BS is not successfully decoded at the indoor user and outdoor users. The outage probability can then be computed as $P_{out} = P_{out,O} + P_{out,I} - P_{out,O} \cdot P_{out,I}$, where $P_{out,I}$ and $P_{out,O}$ are the probabilities of outage at the indoor user and outdoor user, respectively. Defining as $\lambda_{I1}, \lambda_{I2}, \lambda_{O1}$, and λ_{O2} the time fractions allocated to the messages of rates R_{I1}, R_{I2}, R_{O1} and R_{O2}, , respectively, where $\lambda_{I1} + \lambda_{I2} + \lambda_{O1} + \lambda_{O2} = 1$, we elaborate on the calculations of $P_{out,I}$ for the OA scheme. Other calculations follow in a similar fashion. We have

$$
\begin{aligned}
P_{out,I} &= 1 - \Pr\left[R_{I1} \leq \lambda_{I1} C\left(\alpha_I g_{IB} \rho\right),\right. && (32a)\\
R_{I2} &\leq \lambda_{I2} C\left(\left(\alpha_I g_{IB} + \beta_I g_{IH} + \right.\right. \\
&\qquad \left.\left.\left. 2\sqrt{\alpha_I}\sqrt{\beta_I}\, |h_{IB}|\, |h_{IH}|\right)\rho\right)\right]. && (32b)
\end{aligned}
$$

Notice that probability (32b) is the probability of decoding correctly the cooperative message of rate R_{I2} which benefits from beamforming by the BS and HBS.

A. Numerical Results

Fig. 10 plots the probability of outage P_{out} optimized over the backhaul allocation parameter γ and the time allocation parameters versus the SNR ρ for a system with fixed rates $R_O = R_I = 1$ (bits/ channel use), link capacity $C = 0.5$ and $C = 2$ and channel power gains $\alpha_o = -10dB, \alpha_I = -20dB, \beta_o = 10dB$, and $\beta_I = 20dB$. We compare the outage performance of OA and CA with the performance of NF and $C = 0$, as discussed in Sec. V. It is observed that similar performance gains and conclusions can be attained in the downlink as in the uplink when exploiting the HBS-BS backhaul link ($C > 0$) with either CA or OA. In particular, we see that a CA scheme enables reduction of the performance loss with respect to a NF scenario, while an OA approach may improve the overall system performance in terms of outage.

VIII. Concluding Remarks

This paper elaborates on the premise that home base stations (HBSs) may be used as relays for both the subscriber's devices and macrocell users, rather than being used merely as isolated encoders and decoders as in the standard deployment of femtocells. We have studied the advantages of this approach by performing an outage analysis over quasi-static fading channels for specific relaying strategies based on both decode-and-forward and compress-and-forward techniques. Our analysis, mostly focused on the uplink, shows that using a "closed-access" approach the overall performance loss due to the presence of additional indoor users in the femtocell can be overcome if the HBS is used as relay. Moreover, leveraging an "open-access" approach, especially in regimes of low multiplexing gains or sufficiently large outdoor user-HBS channel power gains, operating HBSs as relays is able to even improve the overall system transmission reliability while accommodating also indoor users. Our results also lend evidence to the advantages of communicating soft information via compress-and-forward techniques from the home base station when the backhaul capacity is sufficiently larger than the users' aggregate rate.

Overall, while further analysis in more complex scenarios with multiple cells and users is required for a more thorough assessment, our analysis suggests that the proposed approach is viable and has the potential to greatly improve system performance.

Appendix A

The following region is achievable using CF [9]

$$
\begin{aligned}
R_I &\leq \min\Big\{I(X_I;\hat{Y}_H Y_B|X_O), \\
&\qquad I(X_I;Y_B|X_O) + [C-\Delta]^+\Big\}, && (33a)\\
R_O &\leq \min\Big\{I(X_O;\hat{Y}_H Y_B|X_I), \\
&\qquad I(X_O;Y_B|X_I) + [C-\Delta]^+\Big\}, && (33b)\\
R_I + R_O &\leq \min\Big\{I(X_I X_O;\hat{Y}_H Y_B), \\
&\qquad I(X_I X_O;Y_B) + [C-\Delta]^+, \Big\} && (33c)
\end{aligned}
$$

with $\Delta = I(Y_H;\hat{Y}_H|X_I X_O Y_B)$ and joint distribution $p(x_I)\,p(x_O)\,p(\hat{y}_H|y_H)$. We set X_I and $X_O \sim \mathcal{N}(0,\rho)$ for the transmitted signal, $\hat{Y}_H = Y_H + Q$, where $Q \sim \mathcal{N}(0,1)$ is independent of all other variables, for the quantized relay received signal and obtain (14).

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